2007 Pioneer Award

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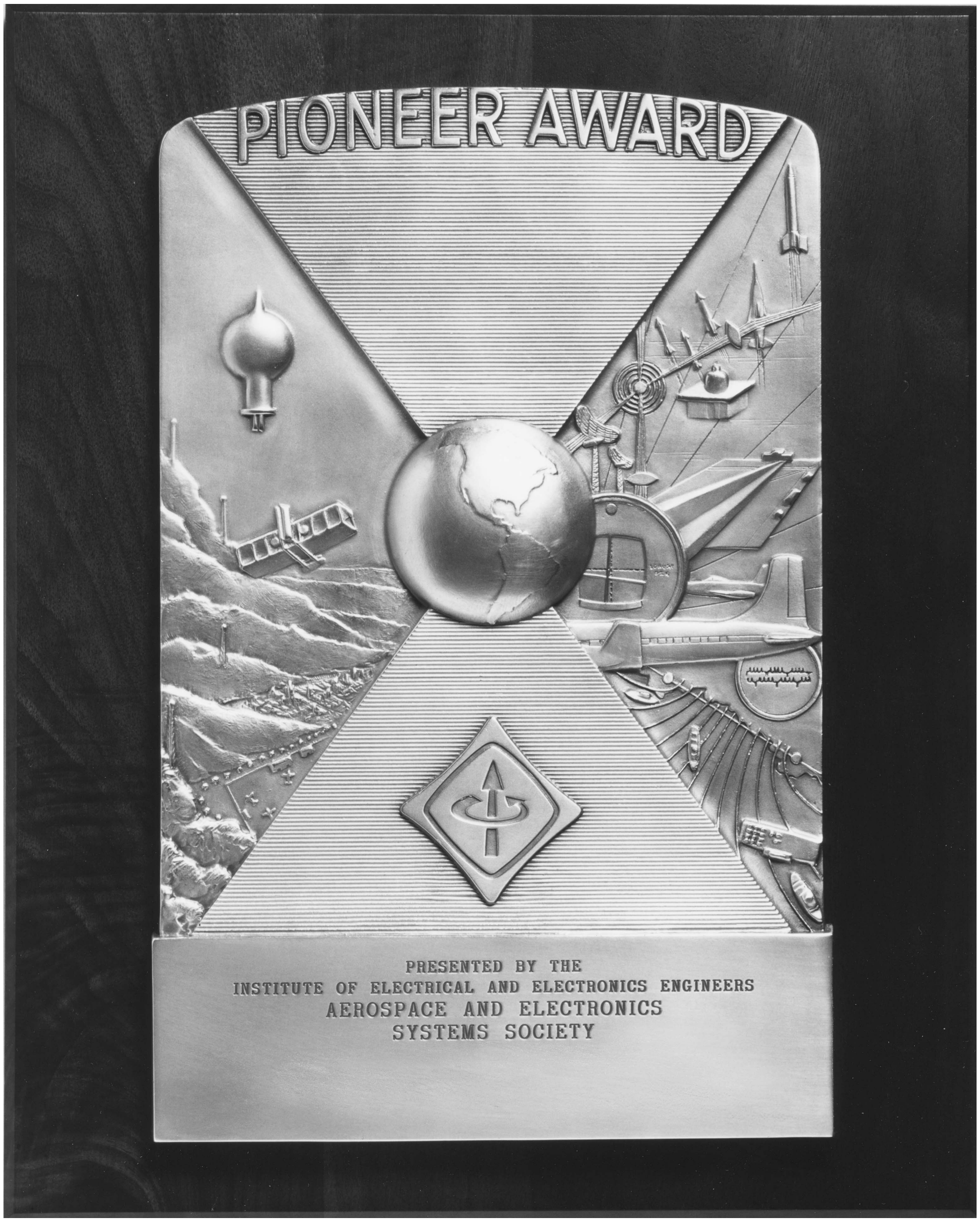

The Pioneer Award Committee of the IEEE Aerospace and Electronic Systems Society has named

GEORGE M. KIRKPATRICK

as the recipient of the 2007 Pioneer Award. The citation reads:

For the original development of monopulse techniques for radar systems.

The award was presented at the International Conference on Radar Systems, Edinburgh, Scotland, October 17, 2007.

George M. Kirkpatrick

George M. Kirkpatrick (S'41—M'45—SM'56—F'65—LF'85) was born in Monmouth, IL, on August 18, 1919. He received the B.S. degree in electrical engineering from the University of Illinois in 1941 and the M.E.E. degree from Syracuse University in 1963.

In 1941 he started a 25 year career with the General Electric Company. During the World War II years he had various assignments, including, 1) assisting in the development and demonstration of an early monopulse tracking radar in the Research Laboratory in Schenectady, NY; 2) the development and installation of an electronic recycler for the Atomic Energy Commission, Manhattan Project, at Oak Ridge, TN; and 3) assistance in the design of the shipboard simulator for the "Cadillac" project at the MIT Radiation Laboratory.

After the war, he taught and supervised the electronics track of the three year GE Advanced Engineering Program which consisted of development engineering assignments accompanied by graduate level academic courses in the fields of microwaves, antennas, control theory and circuits.

In 1947 he joined the GE Electronics Laboratory in Syracuse, NY and became the project engineer for the development of a radar command guidance system for the Hermes A-1 missile. This proportional control system consisted of a modified SCR-584 radar, with an analog computer, an S-band beacon with decoder, and control circuits. After numerous aircraft flight tests, the guidance system was transferred to White Sands, NM and successfully demonstrated with a V-2 rocket launch. The radar guidance concept was applied to the Corporal missile and became operational in Europe. While with the Hermes Project, he was a member of the working group on beamrider and command guidance equipments of the Panel on Guidance and Control of the Research and Development Board.

In 1950, he became manager of a radar section in the GE Electronics Laboratory. He proposed the study of the improvement of angular accuracy to facilitate the design of tracking radars. In particular, this study focused on improved methods of predicting tracking performance and the use of "off-boresight" signals with monopulse radars. The results of this study found wide use in radar design departments, both inside and outside of GE. Other projects in the radar section included coherent MTI, the DPCA for airborne MTI, the monopulse antenna and tracking circuits for an artillery location radar, a sidelooking radar signal processor, and numerous radar studies. Subsequently, in 1956, he was appointed manager of the Equipment and Systems Laboratory, of the GE Electronics Lab, one of the Lab technical divisions. His organization consisted of about 60 professionals and 20 supporting personnel and was composed of four groups: Signal Processing, Communications and Microwave, Guidance Techniques, and Information Processing.

In 1965, Mr. Kirkpatrick transferred to the nearby Syracuse University Research Corporation (SURC) and became a research engineer providing consultation, including foreign travel, for the Foreign Technology Division (FTD) of the Air Force Systems Command. The consultation for FTD was mainly in the area of wide baseline, interferometer, missile guidance systems, but included a variety of tracking radars. In addition to studies for FTD he provided direction for the monopulse modification of an Air Traffic Control radar to improve angular accuracy. He also completed a study for NASA on the use of weather radar in general aviation (GA) aircraft and then served as project engineer for the development and demonstration of an electronic scanned weather radar in a single engine GA aircraft.

A Fellow of the IEEE since 1965, he has served as chairman of the Aeronautical and Navigational Electronics (ANE) Group in 1962–63 and two terms on the Board of Governors of the combined groups which is now the IEEE Aerospace and Electronic Systems Society. He is a licensed Professional Engineer in the State of New York, an Associate Fellow of the American Institute of Aeronautics and Astronautics, a member of Sigma Xi, The Institute of Navigation, and Eta Kappa Nu. He has a current private pilot certificate with more than 4,000 flight hours and MEL, SES and IFR ratings. He has authored (or coauthored) 30 technical papers and reports and holds 10 patents.

Development of A Monopulse Radar System

GEORGE M. KIRKPATRICK, Life Fellow Member

The Pioneer Awardee is requested to present insight into the work accomplished that led to selection for the award. This article was written by George M. Kirkpatrick and is presented to you in his own words.

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The first part of this paper provides background on radar developments at the General Electric (GE) Company in Schenectady, New York. *(Note: The word radar was not used for "radio detection and ranging" until many years later, however, for convenience the word radar is introduced here.)* The object (using available literature and patents) is to show there was an early and continuing effort to develop microwave radar at GE. I was a participant in this radar program during World War II and in particular during the development of a monopulse radar to be described later. No attempt is made in this paper to establish a priority for the work reported.

On June 20 of the year 1922 Marconi made a speech to a joint meeting of the Institute of Radio Engineers and the American Institute of Electrical Engineers in New York City. He included the following often quoted sentences:

> As was first shown by Hertz, electric waves can be completely reflected by conducting bodies. In some of my tests I have noticed the effects of reflection and deflection of these waves by metallic objects miles away.
>
> It seems to me that it should be possible to design apparatus by means of which a ship could radiate or project a divergent beam of these rays in any desired direction, which rays, if coming across a metallic object, such as another steamer or ship, would be reflected back to a receiver screened from the local transmitter on the sending ship, and thereby immediately reveal the presence and bearing of the other ship in fog or thick weather.

From the Marconi speech, and other sources, many engineers undoubtedly recognized the potential of radio waves to detect metallic objects at a distance, though at that time further progress in the development of such detectors was impeded by a lack of suitable components, particularly high frequency transmitters. An early tube development, about 1921, was the result of an investigation of the use of magnetic fields to control electron flow in vacuum tubes by Dr. Albert Hull. Working in the GE Research Laboratory (GERL), Dr. Hull found that a strong magnetic field parallel to a filament and cylindrical anode could control anode current and produce oscillations in an attached circuit. The emphasis at that time was to seek a source of high power at Low Frequencies (LF) for communication purposes. By 1925, a Hull magnetron made at GERL could generate LF power of 15 kW at a frequency of 20 kHz. However, by then, long range communications was shifting to the High Frequency (HF) band. A microwave version of the Hull magnetron, operating at 5.4 cm, was later developed by Chester Rice, Fig. 1.

After the finding (about 1923) that HF signals are useful for long-range communication there was increased interest in the characteristics of the ionosphere. In the United States, Breit and Tuve in 1926 reported on their study of the ionosphere layers. They built an apparatus to sound the ionosphere using

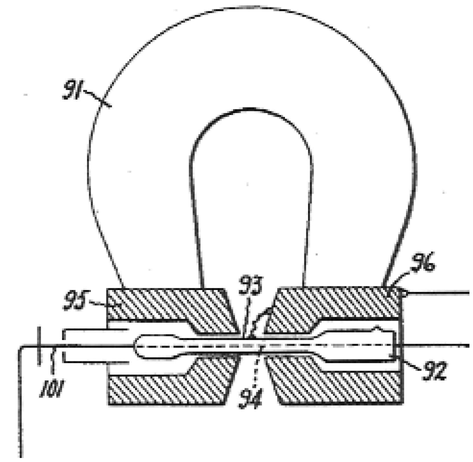

Fig. 1. Cross-section of a 5.4 cm coaxial magnetron as scaled by Rice from the original Hull LF configuration. Rice used this magnetron as a transmitter for his 1935 radar tests.

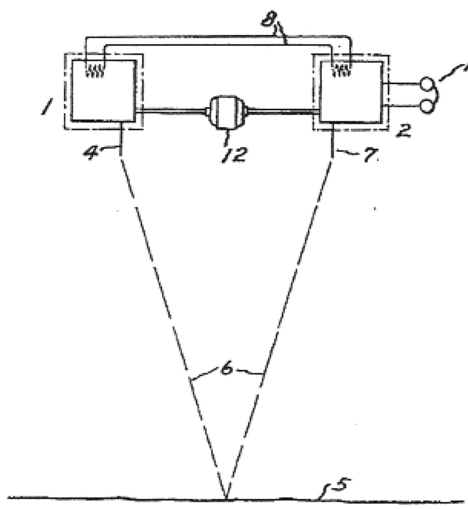

Fig. 2. Conceptual diagram of early FM radar altimeter. From J.O. Bentley Patent 2,011,392.

modulated HF radio signals from a ground-based antenna array. The height was measured by observing the time delay for reception of the modulated signals radiated from the array and reflected from the ionosphere. Various HF frequencies were used in these measurements to enable the creation of a complete picture of the ionosphere as the height of the layers varied with the time of day. Their results were widely followed in the United States and shortly thereafter, in 1928, a patent application was filed by Jetson O. Bentley, for a radio apparatus to measure aircraft altitude. (Fig. 2.) This patent, #2,011,392, assigned to GE, was essentially an inverse of the Breit and Tuve apparatus in that the transmitting and receiving antennas were on the aircraft and the target was the large area of ground under the aircraft. A novel feature of this altimeter was the use of a frequency modulated (FM), gated, transmitter signal.

Chester W. Rice was a prolific inventor who worked for several years, in the GERL,

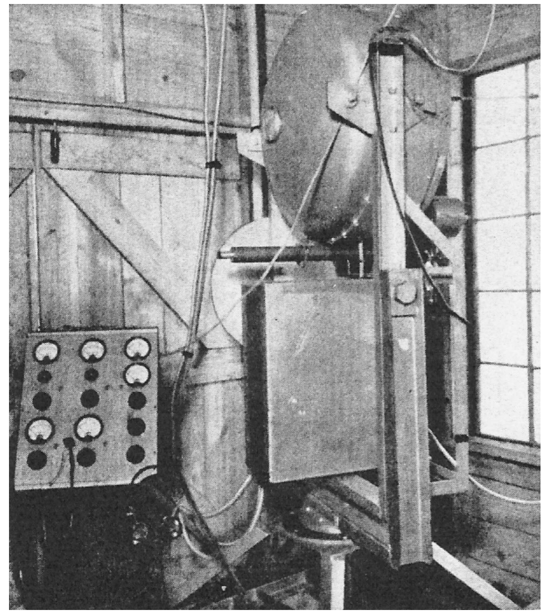

Fig. 3. Picture taken inside the GERL Rooftop Laboratory in Schenectady, NY, showing the transmitter box (center) and the searchlight antenna (top).

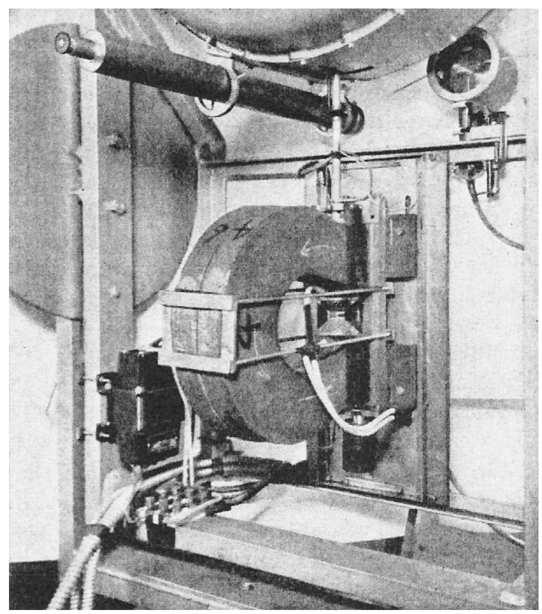

Fig. 4. The 5.4 cm magnetron and the coaxial feed to the antenna. Figs. 3 and 4 are from a *GE Review*, article by Rice, August 1936.

on the application of centimeter (cm) waves to communications and radar. He developed a version of the Hull magnetron (Fig. 1) which enabled him to generate a few watts at a wavelength of 5.4 cm. Using this magnetron power source, he built a microwave transmitter, shown in Fig. 3, and a receiver. The two antennas consisted of modified 24 inch airport searchlights with dipoles mounted at the focal points of the parabolic reflectors. The transmitting dipole was connected to the magnetron transmitter by coaxial line, pictured in Fig. 4, and the receiving

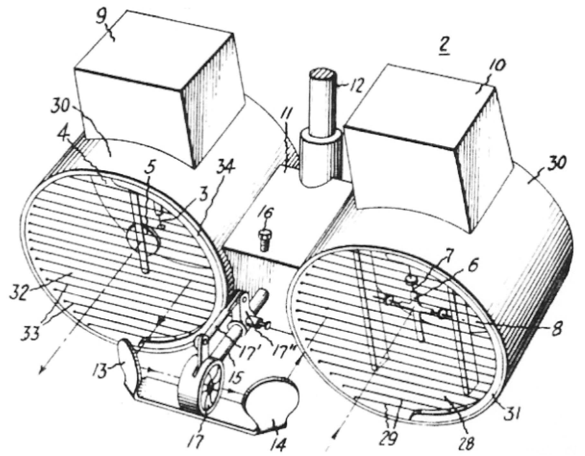

Fig. 5. Antenna arrangement to be placed on an aircraft for Doppler ground speed measurement.

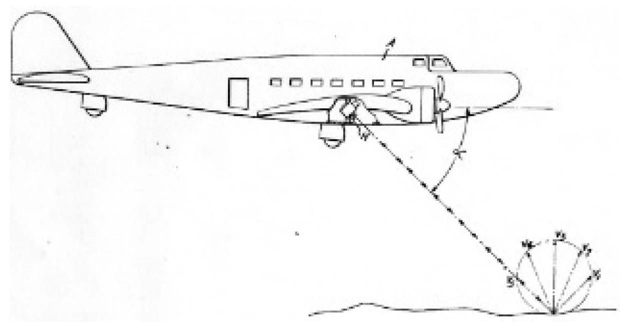

Fig. 6. Conceptual diagram of Doppler ground speed measurement by a radar mounted on an aircraft. Figs. 5 and 6 are from the Rice Patent #2,193,361.

dipole and a miniature triode tube were mounted at the focus of a second reflector. This arrangement produced transmitter and receiver beams with a width of approximately 5 deg. Successful communication experiments were carried out with the transmitter and receiver 6 miles apart.

In 1935, Rice carried out microwave radar experiments by mounting the transmitter and receiver searchlight antennas side-by-side on the rooftop of the GERL laboratory. This arrangement was used for the detection and location of stationary and moving objects by reflected or scattered radiation. From this position, using continuous wave transmissions, moving automobiles on a neighboring road at distances up to one and one fourth mile were detected. Doppler detection was used and resulted from the beats produced between the outgoing transmitter signal and the reflected or scattered radiation returned from a moving object such as an automobile. Interesting results were also obtained when using a small biplane as a target and operating on a radial course. With the plane flying at a speed of 90 mph a Doppler frequency of 1680 Hz was clearly detected out to about 1 mile. Rice reports that he contemplated measuring distances by radar echoes, however, limited resources prevented the further necessary extensive modification of the system required in the transmitter and receiver to use pulses. After the rooftop tests, Rice proposed that his Doppler radar could be placed upon an aircraft and used as a method of measuring the velocity of the aircraft relative to the ground, essentially the inverse of his detection of moving vehicles. Sketches of the configurations of the dual antennas, as drawn in Fig. 5, and with the radar on the aircraft, as pictured in Fig. 6, are taken from his patent 2,193,361 (filed in 1936 and issued in 1940).

During the rooftop radar tests, William C. Hahn joined Rice in the study and improvement of the equipment. Hahn proposed a split-gate range tracker (Fig. 7) using waveforms appropriate for a pulsed

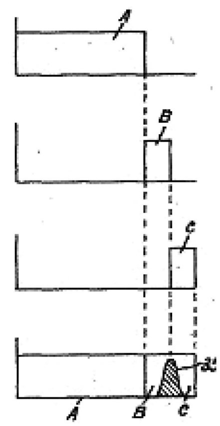

Fig. 7. The working waveforms in the Hahn split-gate range tracker. (a) The time delay to the range gates. (b) The early split-gate. (c) The late split-gate and (#35) the tracked and gated target signal.

radar and subsequently filed a patent application. This application, now patent #2,467,208, was under a secrecy order for some years but was filed in 1943 and issued in 1949 with 37 claims allowed. A complete conical scan radar description incorporating the split-gate range tracker is included in the patent. In addition to the field tests, a number of analytical studies were made by Hahn and others in the GERL of the microwave circuits and components used in the radar. In a 1941 innovative article in the *Journal of Applied Physics*, Hahn described, "A New Method for the Calculation of Cavity Resonators."

A significant early development of the GE laboratories was a planar triode known as the "lighthouse" tube, resulting from its appearance (Fig. 8). This vacuum tube could be used in a receiver as a local oscillator at frequencies as high as 3 GHz. A small pulse radar (the AN/APG-15 with an output of 500 watts) was developed using the 2C46 version of the tube as the transmitter, operating at 2.5 GHz, with the applied pulse voltage considerably beyond the initial specification. The earlier miniature triode used by Rice in the receiver for his 1935 radar tests was essentially a one-dimensional version of the electrodes used in the lighthouse tube. The grid to

Fig. 8. Picture of the GE 2C46 lighthouse tube (mounted on an octal tube base). The disc arrangement of the electrodes favored the use of coaxial circuitry.

cathode spacing was approximately one mil (0.001 inches) and this tolerance was difficult to maintain in the lighthouse prototypes because of the expansion of the mount for the hot cathode. I recall seeing barrels full of rejects during the startup of the production line; the spacing problems were overcome through design and by careful adjustment of the automatic machinery.

While the potential of microwaves to detect metal objects (for example, automobiles and aircraft) had been demonstrated at the GERL as early as 1935, the lack of a definite market was an obstacle to further development of radar at GE. At the same time, secret radar projects were being pursued by the Navy at the Naval Research Laboratory(NRL) and by the Army at the Signal Corps Laboratories. Soon these secret equipments were ready (or nearly ready) for production. At this time the potential of GE (and other companies) for the production of radar equipments was recognized and in August 1940 GE President Charles G. Wilson was invited to send 20 engineers and scientists to NRL to inspect the Navy's secret radar equipment. Other companies also sent engineers and scientists to NRL. Subsequently, GE and other companies received large contracts for the production of Navy and Army radar equipments. Major A. Johnson, a retired GE engineer, has prepared a comprehensive book, *Progress in Defense and Space*, which was published in 1993. Johnson's book is a history of the Aerospace Group, including radar production, of the General Electric Company.

Most (electrical) engineers in industry, at the time large scale radar production was started, had not received courses in microwave theory and had limited exposure to electronics. Using course notes prepared by Dr. Simon Ramo, John Whinnery and others, nearly all of the hundreds of GE engineers working on radar at the GE Company participated in studies of microwave theory as well as electronics. Using these notes, Ramo and Whinnery prepared a book, *Fields and Waves in Modern Radio*, which has been used extensively as a text in college courses.

Returning to the radar work at the GERL: About 1940, a pulsed optical aircraft tracker (now called a lidar) was developed around a 60 inch GE optical searchlight. The arc-light at the focus of the reflector was replaced with a high-voltage, pressurized and triggered spark gap. The reflected signal from the target was received by sensitive phototubes produced in the GERL laboratory by Millard Smith. The return signal was used for closed loop, two-axis, tracking to enable conventional, slaved searchlights to be directed at a target. A rotary power amplifier, the GE Amplidyne©, was used to amplify the tracking signals and subsequently energize the drive motors on the elevation and bearing axes of the searchlights. While the lidar worked well as a tracker, the well known limitations of fog and clouds terminated this development. The lidar was found to be excellent for cloud-height measurements and a field unit was constructed for the Army Signal Corps. Next, an attempt was made to replace the optical source in a searchlight with a microwave source operating at X-band. Using dielectric loading of waveguides, the 4 horn, microwave feed was designed to be nearly a point source at the focus of a 60 inch searchlight. As a result of reducing the size of the four contiguous feeds, there was very little squint (separation) of the four beams of this early, "amplitude" monopulse concept, and the feed structure was put "on-the-shelf" as interest in directing searchlights decreased.

The NDRC (National Defense Research Committee) coordinated radar work in the USA and also with the British. In Volume 1 of the MIT Radiation Laboratory Series, *Radar Systems Engineering*, Louis N. Ridenour, Editor of the series, wrote a section on wartime radar development in the United States, including the following:

> In discussions (1940) with the Microwave Committee of the NDRC, which had been set-up a few months before, members of the British Mission proposed two specific projects which they suggested that the United States undertake: a microwave aircraft-interception equipment, and a microwave position finder for antiaircraft fire control.

The scientists in GERL, with an interest in radar, then directed their efforts toward the first objective, an improved microwave aircraft-interception equipment.

The radar group in GERL obtained an airborne radar, similar to the AN/APG-3, from another division of GE, the Aeronautics and Ordnance Department. This radar was equipped with a Hahn split-gate range tracker and a conical scan antenna. Using the mount and associated tracking circuits from the airborne radar, one of the first monopulse radar systems was built and tested by Blewett, Hansen,Troell and myself at the GERL in Schenectady, NY, in 1942. The new radar was designated as monopulse radar since it was capable of determining range, azimuth and elevation coordinates of a target on each pulse. For several months I worked on the modification and assembly of this dual-plane, tracking radar. The concept of a microwave radar with phase-sensing receiving antennas was originated by Dr. John P. Blewett and

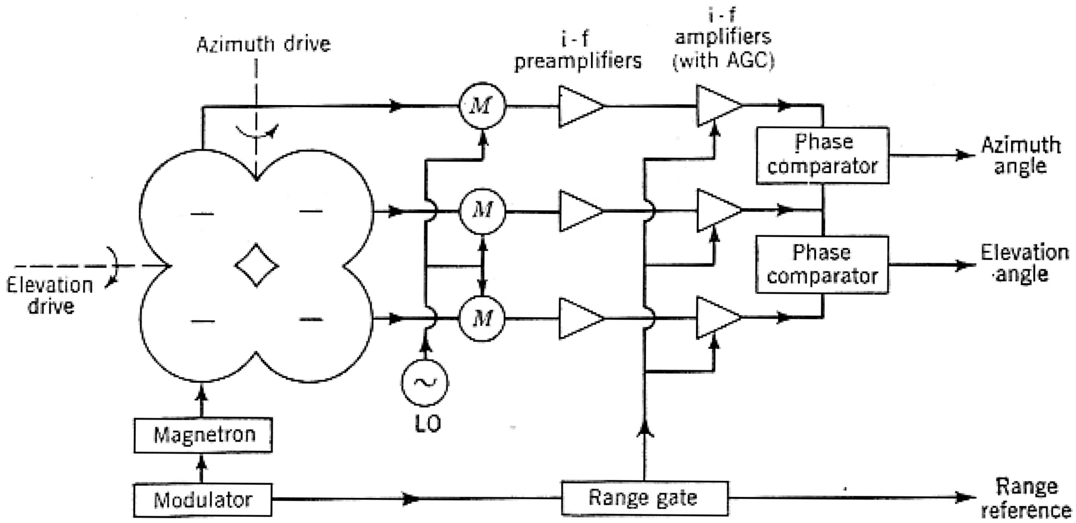

Fig. 9. A “block diagram” of the 1943 monopulse radar. (From an internal General Electric Company report by Blewett, Hansen, Troell and Kirkpatrick.)

Sigfried Hansen. The radar was basically a tracking interferometer, with linear i-f amplifiers with AGC, and sum-and-difference phase comparators for measuring the azimuth and elevation signals (Blewett, U.S. Patent 2,467,361). The radar design is shown in “block-diagram” form in Fig. 9, although the split-gate range tracking block is omitted. The antenna was mounted on the rotating pedestal and consisted of four 16 inch parabolic reflectors cut down and welded together, each with a separate feed at the focal point. One reflector was used to transmit and the other three were paired to receive, two in azimuth and two in elevation with one reflector common to both planes. In this way the duplexing problem was avoided.

Each pair of receiving antennas (Fig. 10) constituted an interferometer with phase centers spaced about 15 inches apart, corresponding to an electrical spacing of about 12 wavelengths at X-band. The beamwidth between the first nulls of the interference pattern was about 4.8 deg, corresponding to a range of phase angles of plus and minus 180 deg. The output of the phase comparator, as a function of the angle off boresight, was non-linear and multivalued for phase values beyond plus and minus 90 deg.

By mixing the three received rf signals with a common local oscillator source, the signals were converted to an intermediate frequency with the relative phases and amplitudes preserved. There was considerable discussion at the time as to the feasibility of maintaining adequate phase stability through conventional intermediate frequency amplifiers. Standard 30 MHz radar i-f amplifiers with 2 MHz bandwidth were used and the phase stability did not turn out to be a problem. The boresight of the radar antenna remained within one angular mil from day-to-day, as measured optically using a distant corner reflector, located in the Sacandaga Hills. In the laboratory environment, an optical telescope was coupled to the remotely mounted antenna with a mechanical linkage and provided accurate indication of the antenna pointing direction.

After the radar was completed and placed in operation, I continued working with the radar to assist in frequent demonstrations and to obtain limited data on the tracking performance. Toward the end of this phase the radar was modified slightly to enable a limited test of off-boresight tracking, thereby taking advantage of a new capability of monopulse radar. Two modifications to the radar were tested (1) pointing at the distant corner reflector and opening the circuit to the tracking servos, and (2) introducing a voltage in an angle tracking circuit and reading the displacement angle in the optical telescope. In the first method, the manual track mode was used to displace the antenna boresight from the target and the phase-detector voltage was plotted as a function of the optical error angle. AGC (automatic gain control) was used to keep the target signal from saturating the i-f amplifiers and the phase comparators and also to normalize the output signal by dividing the error signal by the sum signals.

At this point the GERL monopulse project, after many demonstrations of aircraft tracking, was considered successful and terminated without a further attempt to document the potential of off-boresight tracking. I accepted another assignment in the GE General Engineering Laboratory (GE-GEL) and occupied a desk which had been vacated (he moved to #269) by David Packard, later the HP Company leader (no, I didn’t meet Dave). This assignment consisted of developing an electronic recycler for the secret (Manhattan) project and with a successful demonstration of the recycler at a secret (Oak Ridge, TN) location for Dr. E.O. Lawrence, the project was complete (yes, I did meet Ernest). Next the Laboratory

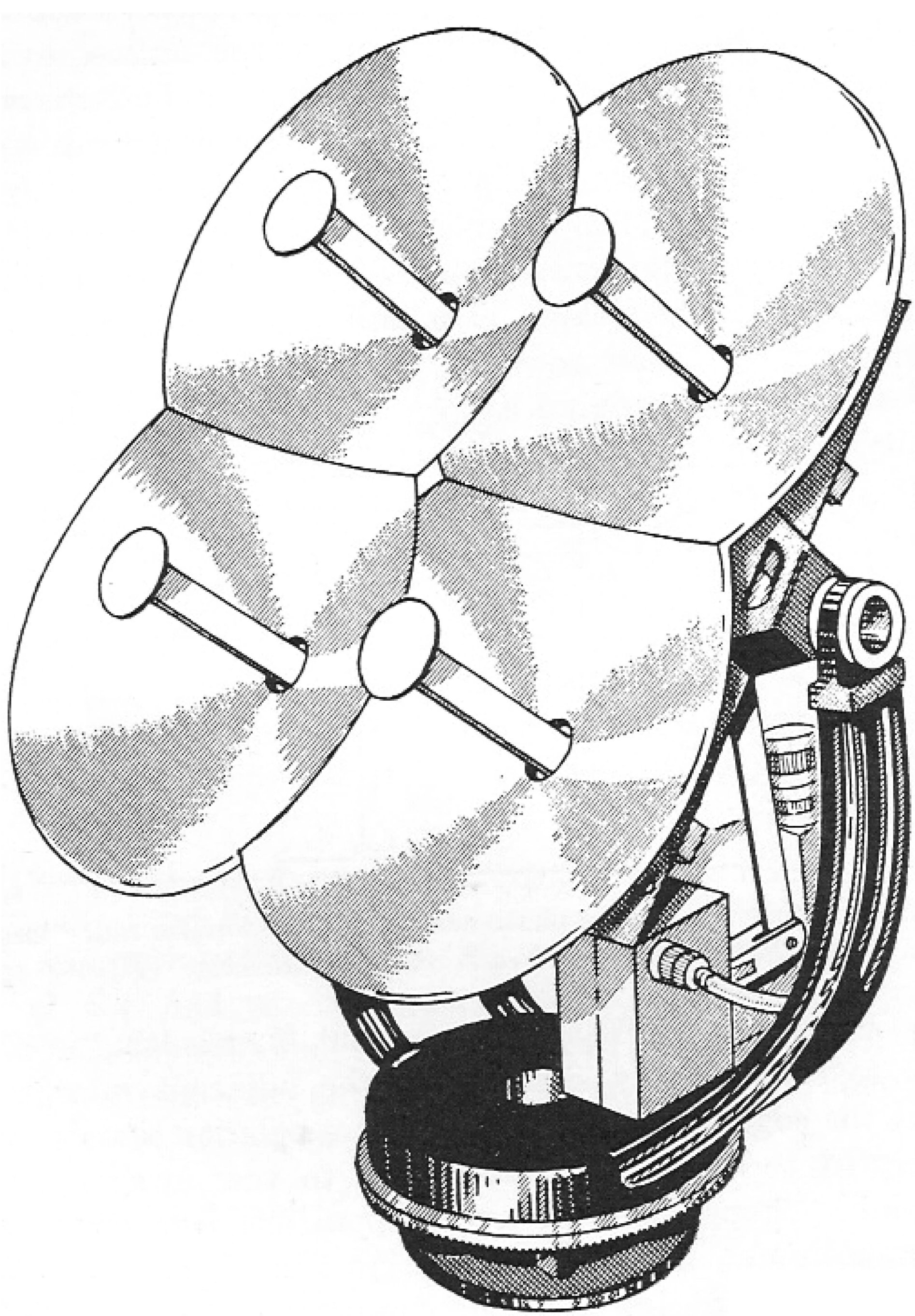

Fig. 10. The tilt-controlled transmitting and receiving antennas of the 1943 General Electric monopulse radar system, shown mounted on a rotating pedestal. (General Electric Co. photograph.)

assigned me to work on the Cadillac Project (AEW) at the MIT Radiation Laboratory. General Electric had engineering teams assigned to the Radiation Laboratory to draft production drawings of both the airborne and the shipboard radars. As a GE employee I was assigned to Dr. Britton Chance's Electronic Time Measurements group, where I assisted David Sayre in the development of a complex and realistic AEW radar simulator to exercise the shipboard equipment.

The War ended about this time and a job opening in the GE Hermes Program, a rocket launching and development program for the U.S. Army, enabled me to become manager for radio guidance. Both radar guidance and precision interferometer developments were underway at a location near the Schenectady, New York GE plant. An existing and available radar, the AN/SCR-584, was modified to provide tracking and guidance to a short-range, ground-to-ground missile, designated the Hermes A-1. The A-1 missile design, in turn, was initially based upon the German Wasserfall (water fall) rocket, a ground-to-air missile. At the same time, a small study was initiated on an interferometer guidance system

for a longer-range, precision rocket, designated the Hermes A-3.

Since the A-1 missile was based upon the already tested Wasserfall design the rocket development proceeded rapidly and there was considerable urgency to complete a prototype of the radar guidance system. The SCR-584 tracking radar was provided to the Hermes Project by the Army and modifications to the radar were developed for the command guidance part of the system. The radar was successfully modified to enable the transmission of multiple S-band pulses for the command guidance signals as well as continued conical scan tracking. The equipment to be placed in the missile consisted of an S-band beacon and signal-processing circuits to decode the guidance signals from the tracking radar. Our breadboard missile circuitry, along with a circularly polarized antenna, was placed on an Army C-45 (Twin-Beech) aircraft (a low-bridge fuselage !) and flight-testing was initiated from the nearby Schenectady County Airport.

From the start of flight-testing it was apparent that the conical scan, with rotating dipole and polarization, was interfering with the guidance signals. I naturally favored the conversion to a monopulse tracker, to be accomplished by major modifications to the SCR-584 radar antenna and receiver, to eliminate the scanning modulation. However, because of time constraints a decision was made to improve the missile circuitry (by Stan Roelofs), also the circularly-polarized receiving antenna (by Ted Bones), and to develop a laboratory simulator (by Bob Morrison) of the conical scan radar signals. Our SCR-584 expert, Jack N. James, proposed a modification to the pulse signal structure which enabled us to meet the desired time schedule. With these measures in place, the flight-testing was resumed and much better results, with little con-scan interference, were obtained. The performance did not have the margin that a monopulse tracker would have afforded the project. The problems on this Hermes development program may seem rather inconsequential in 2008; however, there were a number of missile guidance systems under development back in the decade 1945 to 1955 and many encountered comparable problems. When the guidance system was tested in 1949 on board a V-2 rocket, launched at White Sands Missile Range, the test was reported in the press as the first successful use of closed loop proportional guidance signals. The SCR-584 guidance system, with some modifications, was immediately applied to the Corporal missile and, with crew training at White Sands, was widely emplaced in Europe for several years (until replaced by the Sergeant and then by the inertial guided Pershing missile).

By 1950, GE had completed construction of the Electronics Park near Syracuse, NY and I joined the Electronics Laboratory there as manager of a small radar group. Our charter was to work on problems encountered in the development and production of radar equipments. Monopulse radar had been slow to displace the conical scan approach to angle tracking and here was an opportunity to pursue my earlier interest. So I submitted a proposal to the Army Signal Corps at Ft. Monmouth, NJ with the title, “Angular Accuracy Improvement,” and this rather broad objective was narrowed to the development of off-boresight angle measurements and to finding methods of improving the accuracy of tracking small targets (such as artillery shells).

The off-boresight, monopulse radar tracking study investigated the theory of odd (Δ) and even (Σ) symmetry antenna patterns which when used in appropriate ratio circuitry will give linear signals for off-boresight angles. The output signal was designated an Electrical Correction Signal (ECS) to be added to the antenna mount signals. The study found that if the odd aperture illumination is the spatial derivative of the even aperture function then the ratio of the odd far-field signal to the even far-field signal will be linear (the even aperture field must be zero at the edges of the aperture). Considering one axis, the antenna patterns best suited for tracking single targets, within a range gate, would be a rectangular pattern on the even (Σ) channel and a linear odd pattern on the difference (Δ) channel. The associated antenna aperture functions, together with the far field patterns, are shown in Figs. 11(a)–11(d).

Since the best aperture functions for a linear ECS require extended and impractical apertures, it is necessary to truncate the illuminations to stay within the available aperture dimensions. The truncation issue is best explained by considering the theoretical aperture function that is the Fourier transform mate to the desired far-field pattern exhibiting uniform amplitude with angle over the active angular sector. This Fourier transform is of the $\sin x/x$ form. This is scaled for convenience with a factor of π and also an additional scaling factor, say a, that can be used to adjust the far field pattern to the desired sector width. The resulting aperture function is as follows:

$$g(x) = \frac{\sin(a\pi x)}{a\pi x}$$

where x is the linear aperture coordinate.

The far-field pattern of the aperture function is based on the Fourier transform of the aperture function (for narrow beams), and for the aperture function given above, the Fourier transform turns out to be:

$$G(f_x) = \frac{1}{a} \cdot \mathrm{RECT}\left(\frac{f_x}{a}\right)$$

where f_x is the spatial frequency distribution in the aperture.

The RECT function (Fig. 11(c)) is a square function of unity amplitude and unity width. The

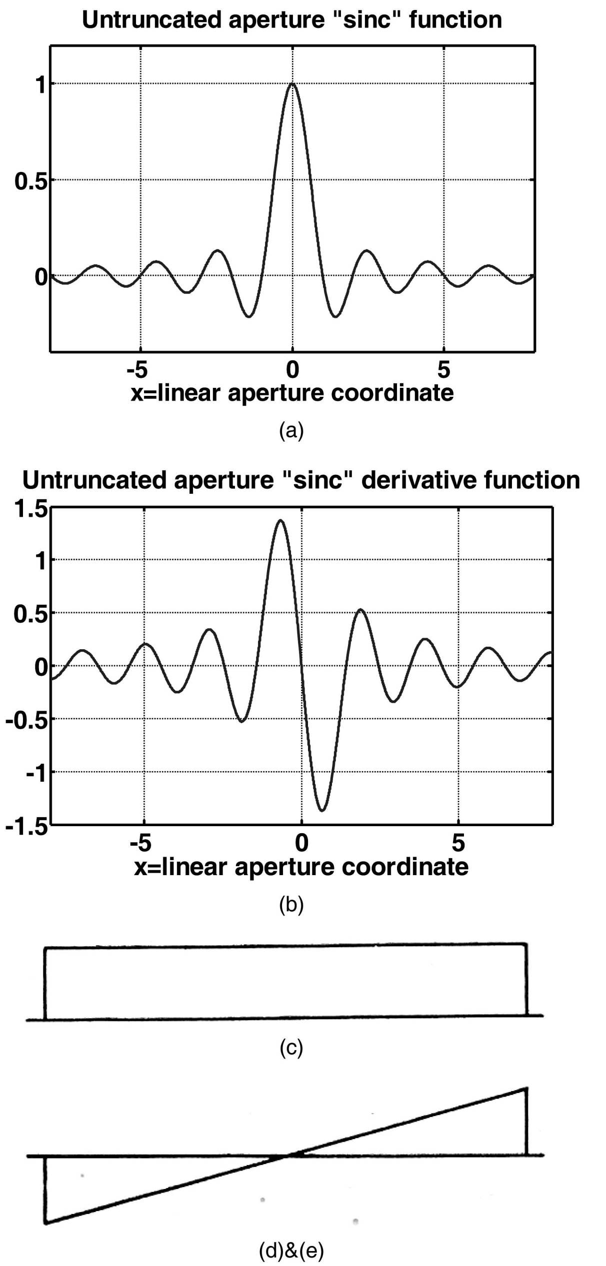

Fig. 11. Aperture illuminations of an infinite aperture, (a) even and (b) odd, and far field patterns (c) even (Σ) far field pattern for the (a) aperture function and (d) odd (Δ) far field pattern for the (b) aperture function, and (e) the ECS ratio (Δ/Σ) of the odd far field (d) divided by the even far field (c).

spatial frequency is related to the far-field radiation pattern angle, say θ, as

$$f_x = \frac{\sin(\theta)}{\lambda}$$

where λ is the radiation wavelength.

If $a = 1$, $g(x)$ becomes, in terms of current mathematical jargon, the “sinc” function, for which all zero-crossings occur at successive integral values. For example, the first zero-crossing or “null” occurs at $x = 1$. This concept will be used to characterize truncations. An infinitely long aperture function is, needless to say, impractical. Figs. 12(a) and 12(b) illustrate truncated even and odd aperture patterns, where both the even and odd functions are truncated at the 3rd null of the even function from the center point in both directions, at the values of $x = \pm 3$. One should note that since the odd pattern is the x-derivative of the even aperture pattern, the odd null corresponds to a zero-slope point or maximum of the even pattern. The far-field patterns that result from these truncations are illustrated in Figs. 12(c) and 12(d). The truncated even and odd aperture functions still give a linear ECS ratio from the far field Fourier functions as shown in Fig. 12(e). These are plotted for the case of truncation at $x = \pm 3$.

For narrow beam antennas, such as are used with a target tracking radar, the ECS ratio (Δ/Σ) of the odd (Δ) to even (Σ) far-field signals can still be linear beyond the three dB beamwidth. An example, based on the even and odd aperture functions being truncated at $x = \pm 1$, (Figs. 13(a) and 13(b)) and the resulting far field patterns, (Figs. 13(c) and 13(d)) gives a nearly linear ECS as shown in Fig. 13(e).

A Nike lens collimator with a four horn, X-band feed (Fig. 14) was used to measure the ECS (Δ/Σ)) for azimuth rotations of a monopulse antenna configuration. The illumination of the lens aperture approximated the aperture functions shown in Figs. 13(a) and 13(b). The resulting azimuth ECS is shown in Fig. 15 for three elevation tilt angles, up, horizontal and down. The lack of symmetry about the vertical axis in the ECS plots is likely caused by a slight feed displacement from the lens and feed center-line.

An important aspect of the accuracy improvement study was to find a standard for angle measurements. The standard reference for gain of an even pattern has been established as the uniform (or rectangular) illumination of the antenna aperture (see Fig. 11(c) for shape of this aperture function). By using the calculus of variations, I found that a linear-odd illumination would produce the maximum signal slope on the boresight axis of a tracking antenna (see Fig. 11(d) for shape of this aperture function). While the uniform illumination produces the highest gain in the far-field pattern, the sidelobe level is undesirably high for most applications and a tapered illumination is better. In a similar manner, the abrupt change at the ends of a linear-odd illumination gives the odd far-field pattern high side lobes and a tapered function is better. For example, for a rectangular aperture, the uniform even illumination gives the well-known first sidelobe level of -13.3 dB while a tapered, cosine-squared gives a -31.7 dB first sidelobe in the far field. Continuing, the pattern produced by a linear-odd illumination has a first sidelobe only 8.44 dB below the first peak of the odd far field pattern while a tapered sine illumination has a -18.2 dB sidelobe. Much study has been devoted to keeping sidelobe levels low on monopulse antennas.

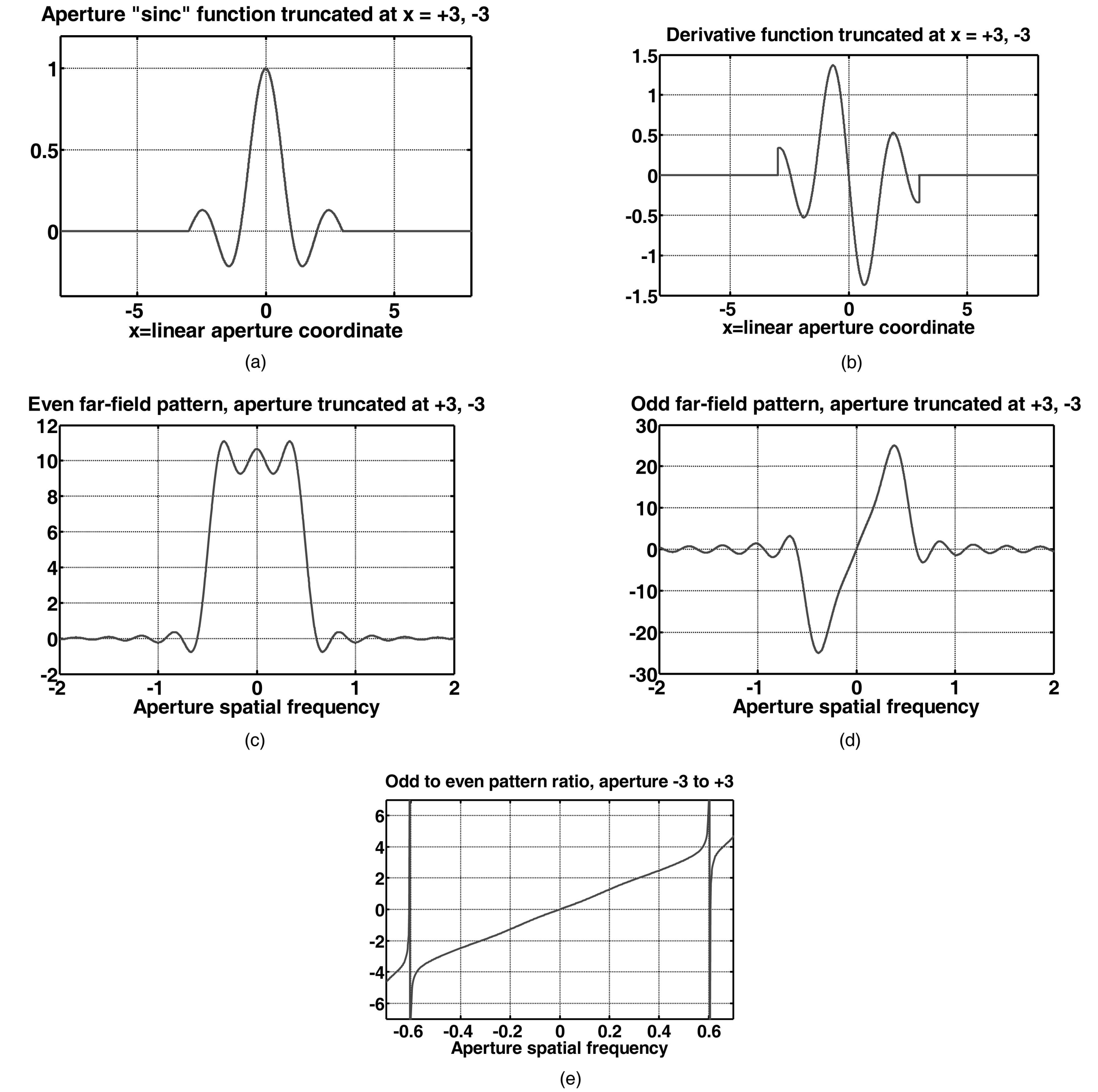

Fig. 12. Aperture illuminations with truncation at -3 and $+3$, (a) even and (b) odd, and far field patterns, (c) even (Σ) and (d) odd (Δ), (e) the ECS ratio (Δ/Σ) of the odd (d) divided by the even (c) far fields. There are singularities at zeroes of the even pattern.

The work on this angular accuracy study (jointly with Otto E. Linderman) from November 1950 through June 1952 was reported in a 127 page report to the U.S. Army, Signal Corps Engineering Laboratories. In addition to completing a contractual obligation, the report was intended to make this information on monopulse radar widely available, and this objective was achieved. The report is included in David Barton's, 1974, *Monopulse Radar*, (Vol. 1 of Radars), Artech House.

The results of the angular accuracy study were applied in the development of the AN/TPQ-5 (Q-5 for short) artillery locating radar (Fig. 16) for the U.S. Army by the GE-GEL laboratory. The Q-5 was designed to give 0.1 angular mil (milliradian) tracking on a 0.001 square meter target (nose aspect of an artillery shell) at a range of 15 km. William Fishbein of the Army's CSTAL Radar Division wrote the following about the Q-5 in our April 2008 *AES Transactions*

> Development of an artillery locating radar began in the middle 1950s. General Electric developed the first experimental radar designed for artillery location, the AN/TPQ-5. This radar used a Foster scanner for search and a mechanical scan for track. Transfer from search to track was rapid enough to enable location of a weapon on a single projectile. The AN/TPQ-5 employed monopulse angle tracking. It underwent extensive testing (at Ft. Sill, OK) with artillery weapons. A location accuracy of 50 meters was achieved at a range of 15 km.

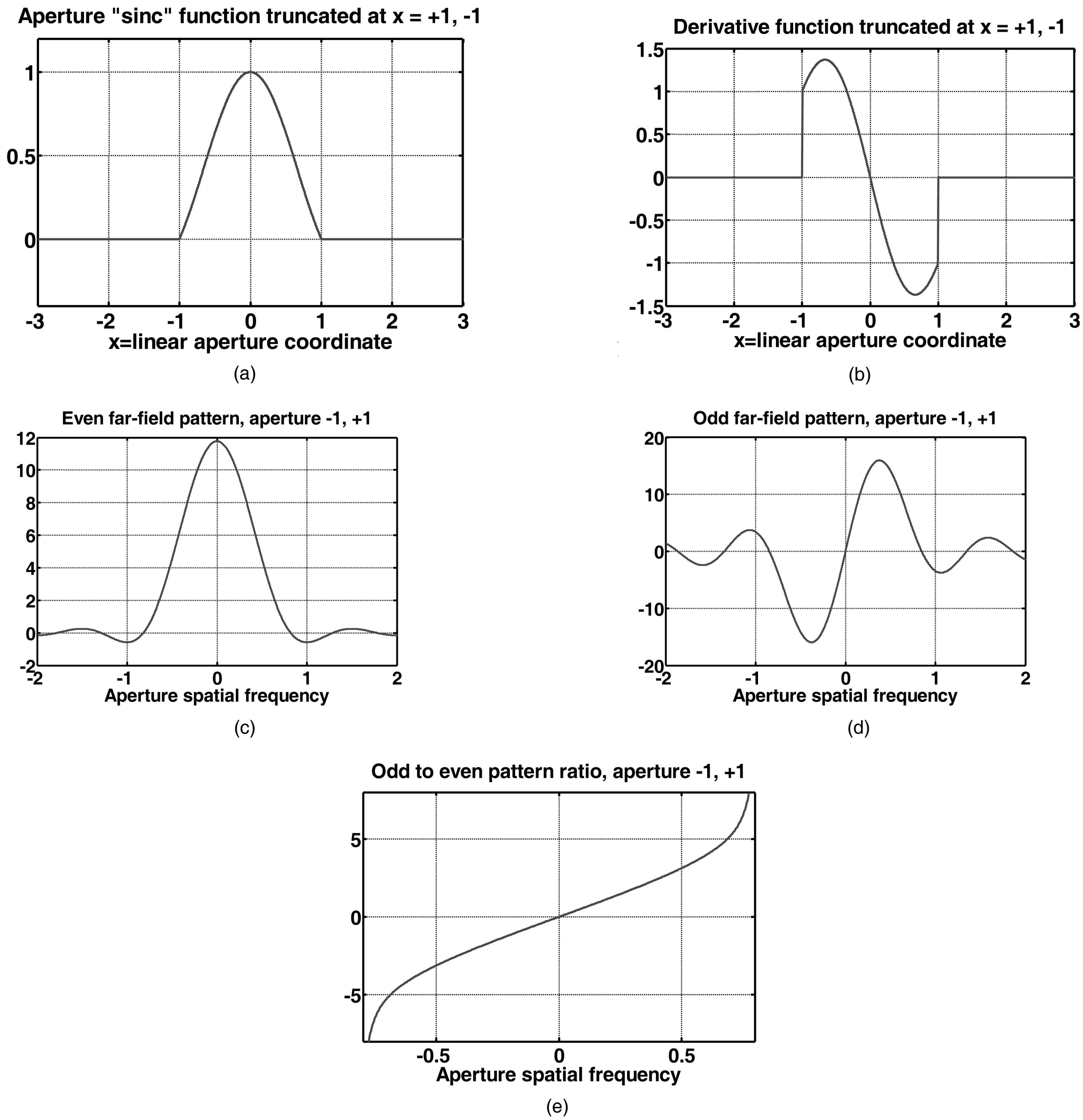

Fig. 13. Aperture illuminations with truncation at -1 and $+1$, (a) even and (b) odd, and far field patterns, (c) even (Σ) and (d) odd (Δ), (e) the ECS ratio (Δ/Σ) of the odd (d) divided by the even (c) far fields.

Major Johnson also included the following on the Q-5 project in his book, *Progress in Defense and Space*

> When the first experimental (Q-5) radar was completed in 1954, the (GE) HMEED Ordnance Radar section took responsibility for radar system testing with a team led by Bob Bockstiegel. Safford North , from Syracuse, took the radar out to Fort Sill, OK for testing with live artillery. Acquisition, tracking and location tests were very satisfactory, but false track-acquisition on anomalous atmospheric targets or "angels" (also sometimes called "goof-balls") were sometimes an annoying problem which was never solved on this (X-band) program. The Army was also quite concerned about the size and weight of the equipment which made transportation to the field difficult.

The study phase of the interferometer guidance system for the Hermes A-3 missile was completed by 1950 and the development of this precision guidance system, with an angular accuracy of perhaps 0.01 mil (milliradian), started at about that time, under the direction of Dr. Lewis J. Neelands. The phase centers of the horn antennas were separated by about 200 wavelengths in the azimuth plane and a lesser separation of perhaps 40 wavelengths in the elevation plane. The horn antennas were mounted on the ends of a rigid cylinder which was in turn mounted on a rotating pedestal. The A-3 guidance was somewhat a magnified (spacing and size) version of the early

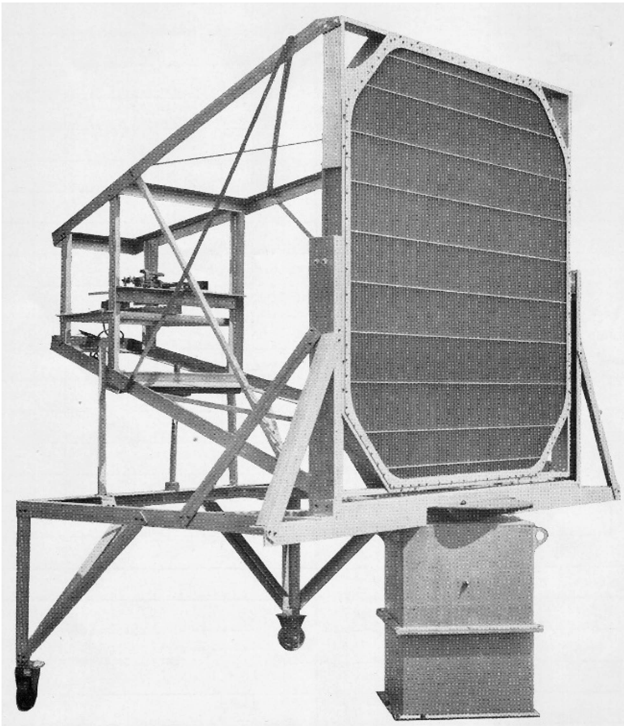

Fig. 14. Oblique view of the X-band monopulse antenna with 4 horn feed used for the electrical correction signal (ECS) (Δ/Σ) measurements.

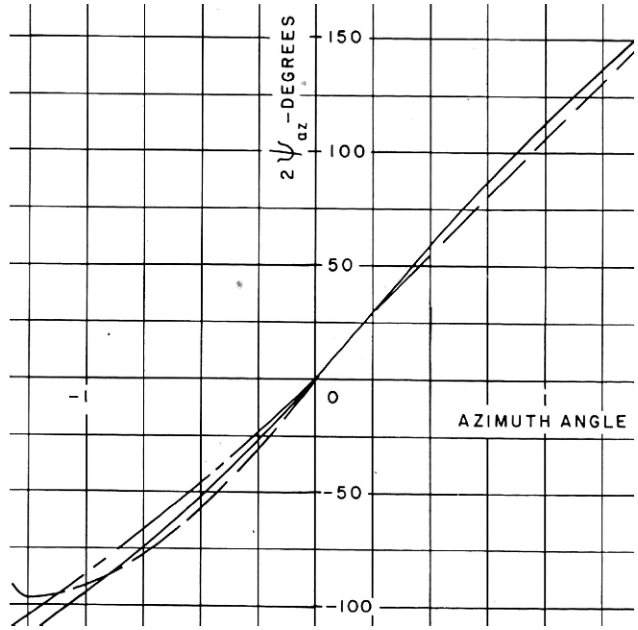

Fig. 15. Measured ECS output of the 4 horn feed with lens aperture as shown in Fig. 16. Solid line is for no tilt, dash line is for 1.15 deg upward tilt, and dash-dot line is for 1.15 degrees down tilt of the beam.

phase-phase monopulse antenna shown in Fig. 10. The A-3 guidance used CW signals and a coherent beacon in the missile to measure range as well as azimuth and elevation angles. Upon completion of the Hermes A-3 missile the guidance system was made operational at the White Sands Proving Ground, NM.

The Hermes A-3 guidance system was followed immediately by the start of an even more demanding radio guidance system for the Atlas missile system. In the new system, the same high accuracy was required for a much longer range missile. The ground station consisted of a monopulse tracker and rate antennas at the ends of several thousand foot baselines. This radio guidance system had excellent performance but later the radio system was dropped for inertial guidance, similar to the fate of the earlier Hermes A-1 guidance radar. However, in this case a modification of the Atlas guidance system became an instrumentation radar (MISTRAM), and was used for many years to evaluate the performance of inertially guided missiles.

At the same time period as the angular accuracy study, the radar group in the GE Electronics Laboratory explored the use of monopulse principles for application to various radar problems. Dr. Frank R. Dickey found that an antenna with monopulse feeds could materially improve the performance of airborne moving target detection (AMTI). The motion clutter at right angles to the ground track of AMTI is largely removed by his Displaced Phase Center Antenna (DPCA) technique. In a similar manner the

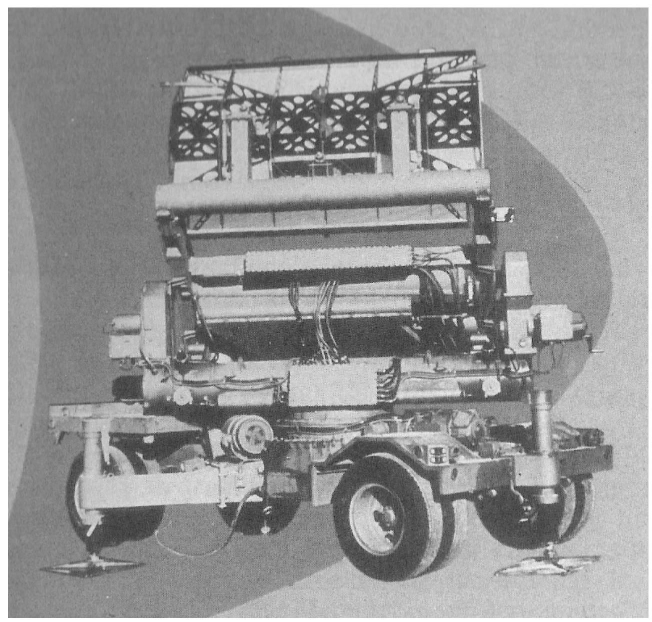

Fig. 16. The AN/TPQ-5 artillery location radar, 1954, with a Foster scanner for search and monopulse for track (rear view). From Johnson, *Progress in Defense and Space*, page 277.

MTI residue of a rapid scan antenna can be essentially removed by his scan compensation technique, also based on monopulse principles. Donald H. Kuhn recognized the value of the double mixing process for his coherent MTI design for monopulse radar and the double mixer became the basis of the sidelobe canceller that originated with Electronics Lab studies.

This concludes my review of a few projects that illustrate the early history of radar at GE and

on the successful development and application of monopulse to many radar problems. I believe that my experience at GE, as reported herein shows that industry recognized the potential of radio waves to detect reflective targets at an early date. When the armed services needed support in the form of advanced components and production capability, industry was ready.

ACKNOWLEDGMENTS

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